Robust Integral of Sign of Error and Neural Network Control for Servo System with Continuous Friction

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Abstract: In this paper, a novel robust controller is proposed for servo mechanisms with nonlinear friction and external disturbance. First, a continuously differentiable friction model is used to represent the nonlinear friction, and neural network (NN) is employed to approximate the nonlinear friction and external disturabance. Then, a novel robust controller is designed by using robust integral of the sign of the error (RISE) term. In order to reduce the measure noise, a desired compensation method is utilized in controller design, in which the model compensation term depends on the reference signal only. The stability of closed-loop is proved based on Lyapunov stability theory, and all signal are proved to be bounded simultaneously. Finally, comparative simulations based on a turnable servo system are implemented to validate the efficacy of the proposed method.

Key Words: Servo mechanisms, friction compensation, desired compensation, robust integral of the sign of the error (RISE) term

1 Introduction

Permanent-magnet synchronous motors (PMSM) have been widely used due to their compact structure, high power density, high torque to inertia ratio and efficiency in many industry applications [1–3]. The linear control method, i.e., proportional-integral-derivative (PID) control methods have been designed for PMSM [4]. Nevertheless, these linear methods can not ensure the dynamic performance of the control system, because the control system exists a lot of model uncertainties and nonlinearities.

The nonlinear control techniques become a natural solution to control the PMSM. With the development of modern control theory techniques, many researchers have proposed some control schemes to control servo system, such as backstepping method [5], robust control [6], adaptive control [7, 8], input-output linearization control [9], sliding-mode control (SMC) [10], and feedback linearization technique. Moreover, the artificial intelligent techniques have also been used for PMSM, e.g., neural network (NN) [11, 12], fuzzy logic system (FLs) [13]. Recently, a new robust control method named integral of the sign of the error (RISE) control scheme has proposed in [14, 15]. The key idea of the RISE is that a unique integral signum feedback term is introduced to against bounded disturbances. This novel control technique has been successfully applied to many filed. In [14], the RISE control technique is used to compensate for uncertainty in class of nonlinear system. In [15], the RISE is employed to handle the continuously differentiable friction model with uncertain nonlinear parameterizable terms. In [16], the RISE is utilized to control an autonomous underwater vehicle, where the RISE is used to compensate for system uncertainties and sufficiently smooth bounded exogenous disturbances. Moreover, the NN technique combined RISE control method have also been used in [17, 18]. Travis [17] introduces NN with a robust integral of the sign of the error feedback and incorporated into backstepping control design to compensate approximate the dynamics of the follower. In [18], NN is used as a feedforward controller that is augmented with a continuous robust feedback term to yield an asymptotic result. Yang [19] proposes a robust integral of neural network and error sign control for MIMO nonlinear system, where NN residual reconstruction error and bounded disturbance are overcome by the integral error signal.

The adaptive robust control method can handle the disturbance and model uncertainties and has been applied to linear motion systems. However, the friction compensation is not considered. In order to compensate the nonlinear friction, it is important to adopt appropriate model model. In the past years, many friction models are used to describe the friction dynamics, such as classical model [20], Armstrong model [21], Dahl model [22], and LuGre model [23]. Among these friction models, the LuGre model is capable of modeling both static and dynamic friction behaviors. It captures most of the friction behaviors, such as Stribeck effect, Hysteresis, Springlike characteristics. Although the LuGre model has been used to compensate friction, there are still some practical issues when using LuGre model, because the LuGre model is not continuously differentiable model. To overcome the shortcoming of the LuGre model, a new continuously differentiable friction model is proposed in [24], the friction model can captures a number of essential aspects of friction without involving discontinuous or piecewise continuous functions. This new friction model has been successfully applied to servo system [25].

Motivated by the above observations, this paper adopt a novel continuously differentiable friction model to represent the friction dynamics, and conjunction with the RISE approach to handle the model uncertainties and external disturbance. The new friction model can capture various friction dynamics, i.e., Coulomb friction, Viscous friction, and Stribeck effects. Then, the friction model and other nonlinear dynamics (model uncertainties, disturbance) are lumped nonlinear, which can be approximated by NN. Moreover, the robust integral of the sign of the error controller is designed

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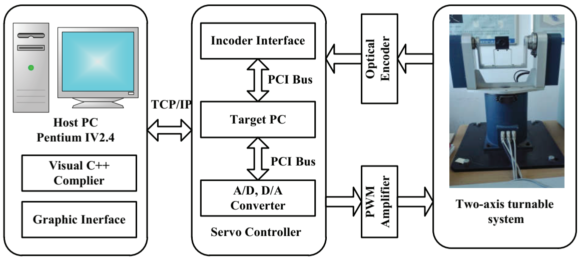

Fig. 1: Schematic diagram of position control for PMSM.

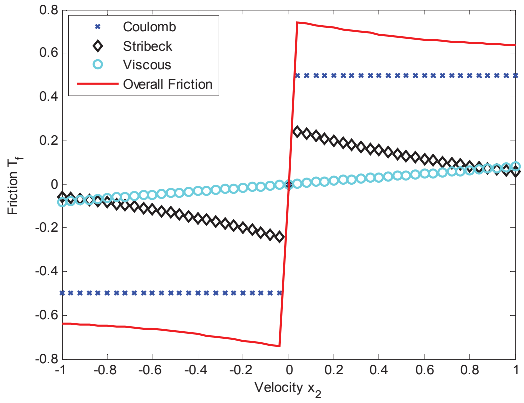

Fig. 2: Friction dynamics of friction model.

by using the reference trajectory. Furthermore, the proposed RISE controller guarantee the an asymptotic output tracking performance even in the presence of friction and external disturbance. Comparative simulations based on a turnable servo system are implemented to validate the efficacy of the proposed method.

The brief is organized as follows: dynamic model and problem formulation is provided in Section 2. Section 3 proposes controller design. Section 4 proves analysis the stability of the control system. Simulations are given in Section 5. Some conclusions are drawn in Section 6.

2 Problem Formulation

2.1 Servo system

In this paper, we consider the a kind of nonlinear turntable servo mechanisms driven by a permanent magnet motor, which model can be written as :

$$\begin{cases} J\ddot{q} + f(q,\dot{q}) + T_f + T_l + T_d = T_m \\ K_E\dot{q} + L_a\dfrac{dI_a}{dt} + R_aI_a = u \\ T_m = K_TI_a \end{cases} \tag{1}$$

where q, $\dot{q}$ are the angular position (rad) and velocity (rad/s), J is the inertia, T_d, T_f, T_l and T_m are the unknown disturbance, load, friction and the driving torque, respectively. $f(q,\dot{q})$ denotes the nonlinear, u is the input voltage, I_a, R_a and L_a are the armature current, resistance and inductance. K_T is the electrical-mechanical conversion constant and K_E is the back electromotive force coefficient.

In practice, if the electrical constant L_a/R_a is small, then the electrical transients $L_a dI_a/dt$ is close to zero.Choose the state vector $x = [x_1, x_2]^T = [q, \dot{q}]^T$, then, the equation (1) can be simplified as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{1}{J}(K_1u - K_2x_2 - T_d - T_l - T_f) \\ y = x_1 \end{cases} \tag{2}$$

where $K_1 = K_T/R$, $K_2 = K_TK_E/R$ are positive constants.

2.2 Friction model

Conventional friction models are discontinuous or piecewise continuous, which may be problematic for deriving smooth control actions. Hence, the off-line identification of friction model parameters is not a trivial task. In this paper, a new continuously friction model is adapted to represent the nonlinear friction.

$$T_f = \alpha_1(\tanh(\beta_1x_2) - \tanh(\beta_2x_2)) + \alpha_2\tanh(\beta_3x_2) + \alpha_3x_2 \tag{3}$$

where α_1, α_2, α_3, β_1, β_2, and β_3 are the positive constants.

Unlike other friction models, equation (3) has a continuously differentiable form to allow more flexible and suitable adaptive control. In (3), $(\tanh(\beta_1\dot{q}) - \tanh(\beta_2\dot{q}))$ denotes the Stribeck effect, $\alpha_2\tanh(\beta_3\dot{q})$ represents Coulomb friction, and $\alpha_3\dot{q}$ is viscous dissipation. For further details regarding the friction model, see [26]. The subsequent development is based on the assumption that x_1 and x_2 are measurable. Fig. 2 provides the profile of friction (3) with parameters $\alpha_1 = 0.25$, $\alpha_2 = 0.5$, $\alpha_3 = 0.08$, $\beta_1 = 100$, $\beta_2 = 1$, and $\beta_3 = 1000$.

Remark 1: Compared to other friction models, (3) has differentiable and smooth operators and thus it can allow for more flexible and suitable adaptive control design and implementation. Thus, in the following section, the differentiable friction model are approximated by using NN, whcih is included inside controller design.

2.3 NN Approximation

To approximate unknown nonlinearities, the RBFNN is employed to approximate the continuous function $Q(Z)$: $R^q \to R$ and can be expressed as follows:

$$Q(Z) = W^T\Phi(Z) + \varepsilon \tag{4}$$

where $Z = [z_1, z_2, ..., z_q] \in R_q$ is the input vector of the NN, $W^T \in R_q$ is a weight vector of the NN. $\Phi(Z) = [\Phi_1(Z), \Phi_2(Z), ..., \Phi_N(Z)]^T$ is the basis function vector and ε is the approximation error of the NN, i.e., $\|W^*\| \leq W_N$, $\|\varepsilon\| \leq \varepsilon_N$ with W_N and ε_N being positive constants. In this paper, a high-order NN (HONN)with basis functions $\Phi_k(Z) = \Pi_{j\in J_k}[\sigma(Z_j)]^{d_k}(j), k = 1, ..., L$ are used with J_k being collections of $L-$ nonordered subsets of $\{0, 1, ..., n\}$, and $d_k(j)$ being nonnegative integers. $\sigma()$ is a sigmoid function $\sigma(x) = a/(1+e^{-bx})+c, \forall a, b \in R^+, C \in R$, where the positive parameters a, b, and real number c are the bounded, slope, and bias of sigmoidal curvature, respectively.

3 Controller design

To address the control of (2), define a set of switching functions as quantities, i.e.,

$$\begin{aligned} s_2 &= \dot{s}_1 + k_1 s_1 \\ r &= \dot{s}_2 + k_2 s_2 \end{aligned} \tag{5}$$

where $s_1 = x_1 - x_d$ is the output tracking error, and k_1 and k_2 are the positive design parameters. In (5), an auxiliary signal error r is defined to get an extra design freedom. It is worth to note that the filtered tracking error r is not measurable since it depends on the acceleration information and is just introduced to assist the following controller design.

The tracking error system can be developed by utilizing the expression (5), we can obtain the following equation

$$\begin{aligned} r = &\frac{K_1}{J}u - \frac{K_2}{J}x_2 - \frac{\alpha_1}{J}(\tanh(\beta_1 x_2) - \tanh(\beta_2 x_2)) \\ &- \frac{\alpha_2}{J}\tanh(\beta_3 x_2) - \frac{\alpha_3}{J}x_2 - (k_1 s_1 + k_2 s_2 - \ddot{x}_d) - d \end{aligned} \tag{6}$$

where $d = (T_l + T_d)$.

In practice, the measure noise may be existed in closed-loop system, since the speed signal is obtained via backward difference of position signal and thus is quite noisy. In the following, we adopted a robust integral of the sign of the error (RISE) control strategy to cancel the noise and model uncertainties by using the desired trajectory information only.

In order to develop the RISE control method, some modifications of r in (6) are written as the following form, with desired trajectories. Thus,

$$\begin{aligned} r = &\frac{K_1}{J}u - \frac{K_2}{J}\dot{x}_d - \frac{\alpha_1}{J}(\tanh(\beta_1 \dot{x}_d) - \tanh(\beta_2 \dot{x}_d)) \\ &- \frac{\alpha_2}{J}\tanh(\beta_3 \dot{x}_d) - \frac{\alpha_3}{J}\dot{x}_d - (k_1 s_1 + k_2 s_2 - \ddot{x}_d) - d \end{aligned} \tag{7}$$

Assumption 1: The uncertainties d is bounded and smooth enough such that $|\dot{d}| \le \delta_1$ and $|\ddot{d}| \le \delta_2$, where δ_1 and δ_2 are positive constants.

To facilitate analysis, auxiliary variable $f_d(x_d, \dot{x}_d, \ddot{x}_d)$ is defined as in (7) depends on $x_d, \dot{x}_d$ are replaced with x_1, x_2. Define function the following function as

$$\begin{aligned} f_d(x_d, \dot{x}_d, \ddot{x}_d) = &\frac{\alpha_1}{J}(\tanh(\beta_1 \dot{x}_d) - \tanh(\beta_2 \dot{x}_d) \\ &+ \frac{\alpha_2}{J}\tanh(\beta_3 \dot{x}_d) + \frac{\alpha_3}{J}\dot{x}_d + \ddot{x}_d - K_2 \dot{x}_d \end{aligned} \tag{8}$$

and the auxiliary function $S(x_1, x_2, x_d, \dot{x}_d, \ddot{x}_d)$ is defined as

$$\begin{aligned} S = &(k_1 s_1 + k_2 s_2) + \ddot{x}_d - \frac{\alpha_1}{J}(\tanh(\beta_1 x_2) - \tanh(\beta_2 x_2)) \\ &- \frac{\alpha_2}{J}\tanh(\beta_3 x_2) - \frac{\alpha_3}{J}x_2 - \frac{\alpha_1}{J}(\tanh(\beta_1 \dot{x}_d) \\ &- \tanh(\beta_2 \dot{x}_d)) - \frac{\alpha_2}{J}\tanh(\beta_3 \dot{x}_d) - \frac{\alpha_3}{J}\dot{x}_d \end{aligned} \tag{9}$$

The function $f_d(x_d, \dot{x}_d, \ddot{x}_d)$ can be approximated by HONN as

$$\begin{aligned} &f_d(x_d, \dot{x}_d, \ddot{x}_d) = W^T \Phi(Z) + \varepsilon \;\; \forall Z = [x_d, \dot{x}_d, \ddot{x}_d] \\ &\dot{\hat{W}} = \Gamma(\Phi(Z)s_2 - \sigma \hat{W}) \end{aligned} \tag{10}$$

Assumption 2: The function reconstruction error ε and its first two time derivatives $\dot{\varepsilon}$ and $\ddot{\varepsilon}$ are bounded.

Equation (7) is written as

$$r = \frac{K_1}{J}u + f_d - S - d \tag{11}$$

Then, the adaptive controller is design as follows:

$$u = \frac{J}{K_1}(\hat{f}_d + \mu) \tag{12}$$

where $\hat{f}_d$ is the NN estimation of f_d, and $\mu(t)$ is the RISE feedback term, which can be designed as :

$$\begin{aligned} \mu(t) = &(k_s + 1)s_1(t) - (k_s + 1)s_1(0) \\ &+ \int_0^t [(k_s + 1)k_2 s_2(\tau) + \beta sgn(s_2(\tau))] d\tau \end{aligned} \tag{13}$$

where k_s and β are the design parameters, and $sgn()$ represents the signum function. The time derivative of (13) is given as:

$$\dot{\mu}(t) = (k_s + 1)r + \beta sgn(s_2) \tag{14}$$

Substituting (12) into (10), the closed-loop tracking error system is given as

$$r = \tilde{f}_d - S - d - \mu \tag{15}$$

where $\tilde{f}_d = f_d - \hat{f}_d$. To facilitate the closed-loop stability analysis, the derivative of (14) is

$$\dot{r} = \dot{\tilde{f}}_d - \dot{S} - \dot{d} - \dot{\mu} \tag{16}$$

Substituting (9) and (14) into (16), one has

$$\begin{aligned} \dot{r} = &\dot{\tilde{W}}\Phi(Z) + \tilde{W}\dot{\Phi}(Z) - \dot{S} - \dot{d} + (k_s + 1)r \\ &+ \beta sgn(s_2) + \dot{\varepsilon} + N(t) - s_2 \end{aligned} \tag{17}$$

where $N(x_d, \dot{x}_d, t)$ represents the following unmeasurable auxiliary term:

$$N(x_d, \dot{x}_d, t) = \dot{\tilde{W}}\Phi(Z) + \tilde{W}\dot{\Phi}(Z) - \dot{S} - \dot{d} + \dot{\varepsilon} + s_2 \tag{18}$$

To facilitate the subsequent analysis, another unmeasurable auxiliary term N_d is defined as following form:

$$N_d = \dot{\tilde{W}}\Phi(Z) + \tilde{W}\dot{\Phi}(Z) \tag{19}$$

From (17) and (19), the closed-loop error system is given as follows:

$$\dot{r} = (k_s + 1)r + \beta sgn(s_2) + \tilde{N}(t) + N_d(t) \tag{20}$$

where $\tilde{N}_d(t)$ is defined as

$$\tilde{N}(t) = N(t) - N_d(t) \tag{21}$$

In a similar manner as in [14], the Mean Value Theorem can be used to develop the following upper bound:

$$\|\tilde{N}\| \le \rho(\|z\|)\|z\| \tag{22}$$

where $z(t)$ is defined as

$$z(t) = [s_1^T, s_2^T, r^T]^T \tag{23}$$

and the bounding function $\rho\|z\|$ is a positive globally invertible nondecreasing function. Then, we have the following inequalities

$$\|N_d\| \leq \zeta_1, \|\dot{N}_d\| \leq \zeta_2 \tag{24}$$

where ζ_1 and ζ_2 are positive constants.

Remark 2: The RISE controller 13 depends on measurable system state x, and the auxiliary error signal $r(t)$ is not used in controller. Moreover, the continuously differentiable friction model is used in controller u, and sign function in $\mu(t)$ via an integral action. Thus, the control input u is continuous, it is better than discontinuous controllers.

4 Stability Analysis

In this section, the stability of the closed-loop system will be analyzed.

Theorem 1: Consider the servo system (2) with NN and RISE controller ensures that all system signals are bounded, and the tracking error converges to zero asymptotically, i.e., $\|s_1(t)\| \to 0$ as $t \to \infty$.

Proof: An auxiliary function $P(t)$ is defined as

$$P(t) = \beta|s_2(0)| - s_2(0)^T N_d(0) - \int_0^t L(\tau)d\tau \tag{25}$$

where β is positive constant.

In (25), the function $L(t)$ is defined as

$$L(t) = r[N_d - \beta sgn(s_2)] \tag{26}$$

The time derivative of $P(t)$ is expressed as

$$\dot{P}(t) = -L(t) = -r[N_d - \beta sgn(s_2)] \tag{27}$$

Thus, the following inequality can be obtained:

$$\int_0^t L(\tau)d\tau \leq \beta|s_2(0)| - s_2(0)N_d(0) \tag{28}$$

Define a continuously differentiable positive function V as

$$V = \frac{1}{2}s_1^2 + \frac{1}{2}s_2^2 + \frac{1}{2}r^2 + P + Q \tag{29}$$

In (29), Q is defined as

$$Q = \frac{1}{2\Gamma}\tilde{W}^T\tilde{W} \tag{30}$$

where $\tilde{W} = \hat{W} - W$.

Now, it is important to observe that V exists the following inequalities

$$U_1(y) \leq V \leq U_2(y) \tag{31}$$

where $y = [s_1, s_2, r, \sqrt{P(t)}, \sqrt{Q(t)}]$, and $U_1(y)$, $U_2(y)$ are defined as

$$U_1(y) = \lambda_1\|y\|^2,\ U_2(y) = \lambda_2\|y\|^2 \tag{32}$$

where λ_1 and λ_2 are positive constants.

Then, differentiating (29), $\dot{V}$ can be expressed as

$$\begin{aligned}\dot{V} &= s_1\dot{s}_1 + s_2\dot{s}_2 + r\dot{r} + \dot{P}(t) + \dot{Q}\\ &= s_1(s_2 - k_1 s_1) + s_2(r - k_2 s_2)\\ &+ r\big(-(k_s+1)r - \beta sgn(s_2) + \tilde{N}(t) + N_d(t) - s_2\big)\\ &- r[N_d - \beta sgn(s_2)] + \tilde{W}\Phi(Z)s_2 - \sigma\tilde{W}\hat{W}\end{aligned} \tag{33}$$

$\dot{V}$ can be simplified as follows

$$\begin{aligned}\dot{V} =& r\tilde{N}(t) - (k_s+1)\|r\|^2 - k_2\|s_2\|^2 - k_1\|s_1\|^2\\ &+ s_1 s_2 - \sigma\tilde{W}\hat{W}\end{aligned} \tag{34}$$

By the following inequalities, one has

$$2s_1 s_2 \leq s_1^2 + s_2^2 \tag{35}$$

and the following inequality holds

$$|r\tilde{N}| \leq \rho(\|z\|)\|z\||r| \tag{36}$$

Then, (32) can be written as

$$\begin{aligned}\dot{V} \leq& \big[\rho(\|z\|)\|z\||r| - (k_s+1)\|r\|^2\big] - (2k_1-1)\|s_1\|^2\\ &- (k_2-1)\|s_2\|^2 - \sigma\bigg(\|\tilde{W}\| - \frac{\|W\|}{2}\bigg)^2 + \frac{\|W\|^2}{4}\\ \leq& \big[\rho(\|z\|)\|z\||r| - (k_s+1)\|r\|^2\big] - (2k_1-1)\|s_1\|^2\\ &- (k_2-1)\|s_2\|^2 - \sigma\bigg(\|\tilde{W}\| - \frac{\|W\|}{2}\bigg)^2\\ \leq& -U(y)\end{aligned} \tag{37}$$

where $U(y) = c\|z\|^2$ is a positive semidfinition function and c is a positive constant.

According Barbalat's lemma [27], we can conclude that

$$r(t) \to 0 \; as \; t \to \infty \tag{38}$$

Furthermore, based on the definition of $r(t)$, one has

$$s_1(t) \to 0 \; as \; t \to \infty \tag{39}$$

The proof is completed.

Remark 3: Results of Theorem indicate the proposed robust controller can handle the model uncertainties, which has the following advantages, one is the RISE controller is only depended on the reference trajectory. Another is the measurable noise is reduced.

Remark 4: In Theorem, it is notice that the RISE controller must satisfy the following prerequisites. 1) The model uncertainties and external disturbance are smooth enough, Assumption 1 and Assumption 2 are satisfied. 2) The controller gains k_1, k_2 and k_s are chosen large enough.

Remark 5: The NN output is incorporated into integral term (13). Thus, the reconstruction error is compensated by robust term.

5 Simulation Results

In this section, the extensive simulations are used to illustrate the the effectiveness of the proposed control scheme. The parameters of the servo system (1) are given as $J = 0.1kg/m^2$, $K_E = 0.2V/(rad/s)$, $K_T = 5N \cdot m/A$, $R = 5\Omega$, $T_l = 0.1N \cdot m$, and thus $K_1 = K_T/R = 1$, $K_2 = K_E K_T/R = 0.2$, $\beta_1 = 700, \beta_2 = 15, \beta_3 = 1.5$, $\alpha_1 = 0.02, \alpha_2 = 0.01, \alpha_3 = 0.2$.

In order to illustrate the effective of the proposed control method, the following two controllers are compared in simulation.

1) RISE controller: This is the proposed RISE control method with friction model. The friction model is given as

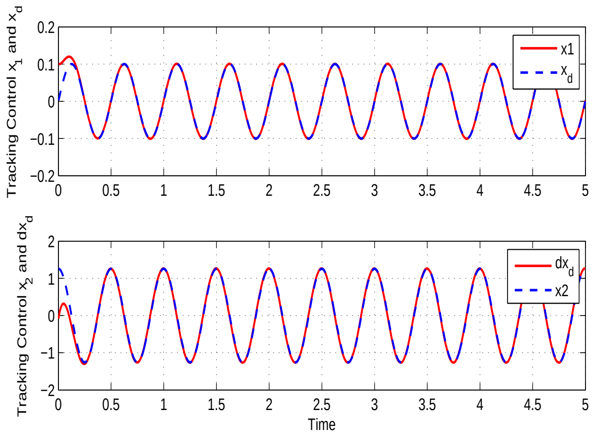

Fig. 3: Simulation results for motor position and speed of RISE.

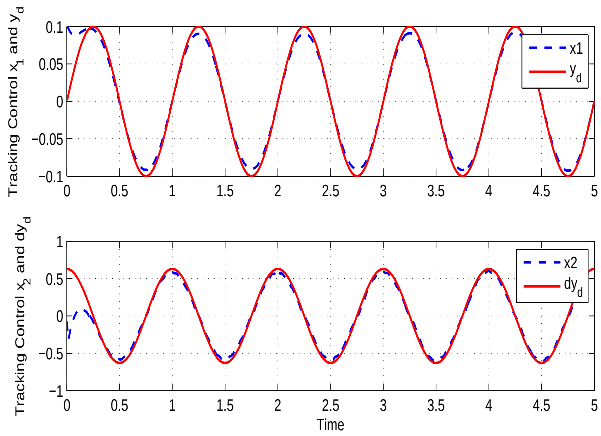

Fig. 4: Simulation results for motor position and speed of PID.

(3). The controller parameters are chosen as $k_1 = 10, k_2 = 1, k_s = 0.5, \beta = 0.001$.

2) PID controller: This is the proportional-integral-derivative controller with position feedback. The controller is $u = k_p(x_1 - x_d) + k_i \int_0^t (x_1 - x_d) + k_d d(x_1 - x_d)/dt$. The controller gains $k_p = 10$, $k_i = 1$, $k_d = 5$ are tuned for a given position reference $x_d = 0.1sin(4\pi t)$, to make a tradeoff between the steady-state performance and transient performance.

The simulation results are depicted in Figs. 3-4. Fig. 3 shows the position and speed tracking of proposed control scheme, and Fig. 4 describes the effective of the PID control method. From the Figs. 3-4, one can see that the tracking effect of the RISE is better than the PID. This is due to the RISE controller contains robust term, which against the model uncertainties and external disturbance.

6 Conclusion

In this paper,we proposed a robust controller with NN and integral of the sign of the error term for servo mechanisms with friction dynamics. A continuously differentiable friction model is used to represent the friction dynamics (i.e., Coulomb friction, Viscous friction and Stribeck effect), which is compensated by using NN. Then, a novel robust controller is designed by using robust integral of the sign of the error. In order to reduce the measure noise, a desired compensation method is utilized in controller design, in which the model compensation term depends on the reference signal only. The stability of closed-loop system is proved by Lyapunov stability theory. Comparative simulations based on a turnable servo system are implemented to validate the efficacy of the proposed method.

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